Renewable and Sustainable Energy Reviews 13 (2009) 2295–2308

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Exergoeconomic analysis and optimization of combined heat and power production: A review

Aysegul Abusoglu, Mehmet Kanoglu *

Department of Mechanical Engineering, University of Gaziantep, 27310 Gaziantep, Turkey

ARTICLE INFO

Article history:
Received 6 January 2009
Accepted 26 May 2009

Keywords:
Exergoeconomics
Thermoeconomics
Combined heat and power
Optimization

ABSTRACT

Exergoeconomics is also called thermoeconomics, and thermoeconomic analysis methodologies combine economic and thermodynamic analysis by applying the cost concept to exergy which accounts for the quality of energy. The main concept of thermoeconomics is the exergetic cost and it deals with cost accounting methods. This paper is a review on the exergoeconomic analysis and optimization of combined heat and power production (CHPP). A brief historical overview on the exergoeconomics analysis and optimization is given. The concept of exergetic cost and cost accounting methods are discussed. An application of relevant formulation is given using a diesel engine powered cogeneration system as an example. Main thermoeconomic methodologies available in literature are described and their advantages and disadvantages with respect to one another are compared and discussed through a well-known problem, namely CGAM. Important studies on thermoeconomic analysis and optimization of combined heat and power production are listed based on the methodology used and the type of system considered.

Contents

* Corresponding author. Tel.: +90 342 3172508; fax: +90 342 3171104.
E-mail address: kanoglu@gantep.edu.tr (M. Kanoglu).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2009.05.004

Nomenclature

c	cost per unit of exergy ($/GJ)
$\dot{C}$	cost rate associated with exergy ($/h)
$\dot{E}$	exergy rate (kW)
$\dot{E}_{dest}$	rate of exergy destruction (kW)
$\dot{E}_{heat}$	rate of exergy transfer by heat (kW)
f	exergoeconomic factor (%)
h	enthalpy (kJ/kg)
I	investment cost ($)
L	Lagrangian
$\dot{L}$	rate of the Lagrangian
Π	exergoeconomic cost vector (kW)
r	relative cost difference (%)
$\dot{S}$	entropy rate (kW/K)
$\dot{Q}$	rate of heat transfer (kW)
$\dot{W}$	power (kW)
x	vector of decision variables
y	vector of all the inputs and outputs
Y	constraint function
$\dot{Z}$	cost rate associated with the sum of capital investment and O&M ($/h)

Abbreviations

TADEUS	thermoeconomic analysis for diagnosis of efficiency reduction in systems
DEPC	diesel engine powered cogeneration
TEC	theory of the exergetic cost
TECD	theory of the exergetic cost—disaggregation methodology
TFA	thermoeconomical functional analysis
EEA	exergoeconomical analysis
SPECO	specific exergetic cost analysis method
AVCO	average exergetic cost analysis method
MOPSA	modified productive structural analysis method
LIFO	last in first out principle
EFA	engineering functional analysis
STT	structural theory of thermoeconomics
C	compressor
AP	air preheater
T	turbine
CC	combustion chamber
Ev	evaporator
Ec	economizer
HRSG	heat recovery steam generator

Greek letters

η	energy efficiency
ε	exergy efficiency
β	capital recovery factor (%)
λ	vector of all the Lagrange multipliers
τ	number of units and junctions
ω	number of units, junctions and branching points

Superscripts

BQ	steam
CHE	chemical
P	mechanical
T	thermal
W	work or electricity

Subscripts

av	average
D	exergy destruction
F	fuel
i	any stream
in	streams entering a component or system
k	any component
mar	marginal
out	streams leaving a component or system
P	product
tot	total plant

1. Introduction

Exergoeconomics (thermoeconomics) combines exergy analysis with conventional cost analysis in order to assess and improve the performance of energy systems [1]. The primary contribution of an exergy analysis to the evaluation of an energy system comes through a thermoeconomic evaluation which considers not only the inefficiencies but also the costs associated with these inefficiencies and the investment expenditures required to reduce them. The objective of a thermodynamic optimization is to minimize the thermodynamic inefficiencies within the system, whereas the objective of a thermoeconomic optimization of a system is to estimate the cost-optimal structure and the cost-optimal values of the thermodynamic inefficiencies in each component [2–4].

In this paper, starting from earlier pioneer works in the area of thermoeconomics, major contributions are summarized. By detailed search with appropriate keywords, a researcher can easily reach to the related papers in the open literature. First, a short historical overview on the exergoeconomic analysis and optimization of thermal systems is given. In the following sections, exergy costing and cost accounting concepts are described. Various thermoeconomic methodologies are discussed and exergoeconomic analysis and optimization of combined heat and power production are presented.

2. Historical overview

The idea of coupling exergy and cost streams was first discussed by Keenan in 1932 [5]. He pointed out that the value of the steam and the electricity rests in the "availability" not in their energy [6–8]. In the late 1950s, the studies of second law costing started in two different places independently. Tribus and Evans [6] studied desalination processes by exergy analysis, which led them to the idea of exergy costing and its applications to engineering economics, for which they coined the word "*thermoeconomics*" [9]. The concept of their procedure was to trace the flow of money, fuel cost and operation and amortized capital cost through a plant, associating the utility of each stream with its exergy. In the late 1960s, El-Sayed connected with Evans and Tribus in their research on desalination and they published one of the important papers in the subject in 1970, in which the mathematical foundation for thermal system optimization was given [10]. Another study on their idea was performed by Reistad who applied the method of El-Sayed and Evans to a simple power plant, comparing that approach with conventional optimization procedures [11]. Also in 1960s, Gaggioli studied the optimal design of power plant steam piping and its insulation in his Ph.D. thesis. He proposed costing

steam exergy at a value to that of power produced, penalizing exergy destructions and losses for the electricity which therefore would not be produced [12].

In Europe, many important works on the second law analysis methodologies and on "exergy" itself were performed in late 1950s and during 1960s and 1970s [13–20]. Bergmann and Schmidt assigned costs to the exergy destruction in each component of a steam power plant and optimized feed water heaters [17]. Szargut used exergy costing procedure in the analysis of a simple cogeneration plant by derivation of an approximate generalized formula and introduced ecological cost coefficient into the literature. The use of this coefficient made the determination of cumulative consumption of non-renewable natural resources in a production process possible [18–20]. Some of these works were on thermoeconomic analysis and collected in a book in 1985 by Kotas [21], which is still accepted as one of the basic references in exergy analysis and thermoeconomics of thermal systems.

Although there had been numerous studies and theoretical approaches in the field of thermoeconomics, the methodological and functional applications of it to the analysis, design and optimization of thermal systems comprehensively did not start until 1980s. During this decade, the interest and studies related to exergoeconomic analysis techniques and applications have increased considerably. Frangopoulos [22–27] and von Spakovsky [26–30] applied and formalized the first autonomous method developed by Evans and El-Sayed [10]. Tsatsaronis introduced some key concepts of thermoeconomics such as *Fuel and Product* [31]. Valero et al. published another key paper on thermoeconomics and presented the basic methodology related to exergy based cost analysis and applications [32] and with Lozano, he presented basics and several applications of the theory of exergetic cost, a major cornerstone approach to the field of thermoeconomics [33].

The major contributions were done in 1990s, to achieve a greater standardization and formalism in the area of thermoeconomic studies. The common idea was to propose a standard and common mathematical formulation for all thermoeconomic methodologies employing thermoeconomic models that can be expressed by linear equations [34]. At that time, Tsatsaronis proposed the term "*exergoeconomics*" which was defined as a part of thermoeconomics. Since the latter have been used in a general sense expressing the interaction between any thermodynamic variables and economics, he suggested that exergy based cost accounting methodologies should be indicated by exergoeconomics [35]. One of the most interesting works was the CGAM problem [36–40] developed originally by Frangopoulos, Tsatsaronis, Valero and von Spakovsky. The CGAM problem was named after the first initials of the participating investigators. The objective of the problem was to show how the methodologies were applied, what concepts were used and which results were obtained in a simple and specific problem [36]. The sequential papers published in the same issue had the common definitions of the physical, thermodynamic and cost models plus the objective function but different procedures of thermoeconomic optimization. The authors emphasized that the aim of the presented work was the unification of thermoeconomic methodologies, not a competition among them. Another important project called TADEUS (in honor of Tadeus Kotas [21]) was initiated in 2001 [41–43]. The major goals of that project were to apply procedures from different research groups in thermoeconomic analysis to the diagnosis of the energy system malfunction and inefficiencies and to establish the common concepts and nomenclature and compare the results and highlight the main characteristics of each approach.

Since 1980s, there have been numerous published papers all around the world on exergoeconomic cost analysis, application and optimization of thermal systems. Good fractions of them have been published since mid-90s due to the improved structural formalism of the exergoeconomic methodologies [44–81]. Exergoeconomic studies have been successfully applied to power plants, combined heat and power production or cogeneration facilities [45–47,50,51,54,57,59–81]. Progressed innovative methodologies of fuzzy logic and genetic algorithm methods have also been applied to existing power plants and cogeneration facilities since late 1990s [47,59,69].

3. The cost of exergy and exergoeconomics

The exergy cost of a mass or energy stream is the amount of exergy required to produce it. In the case of a cogeneration plant, the exergy cost of the net power is the exergy provided by fuel to generate the electrical power delivered to the network by the cogeneration plant [33–39]. When analyzing the cost structure of a system, one can distinguish between average costs and marginal costs [1–3,33]. Average costs are ratios and express the average amount of resources per unit of product, and can be defined mathematically as [2,8,21,33]

$$c_{av,i} = \frac{\dot{C}_{av,i}}{\dot{E}_i} \tag{1}$$

where $c_{av,i}$ is the unit specific average cost of the ith stream, $\dot{C}_{av,i}$ and $\dot{E}_i$ represent the exergetic cost and exergy of the ith stream, respectively. Marginal costs are derivation and indicate the additional resources required to generate one or more units of product under specified conditions. Mathematically, it is defined as [33]

$$c_{mar,i} = \frac{\partial \dot{C}_i}{\partial \dot{E}_i} \tag{2}$$

Since the average cost is not predictive, it can only be known after production process, when we know how much resources were used. On the other hand, marginal costs are predictive in nature; they can be used to calculate additional fuel consumption when the production is modified. Thermoeconomic optimization methods are generally based on the marginal costs while average costs are used in the exergoeconomic analysis of the systems [32–34]. In exergy costing, a cost is associated with each exergy stream. Exergy transfers by the entering and exiting streams of matter and by power and heat transfer rates may be written, respectively as [2]

$$\dot{C}_i = c_i \dot{E}_i \tag{3}$$

$$\dot{C}_e = c_e \dot{E}_e \tag{4}$$

$$\dot{C}_w = c_w \dot{W} \tag{5}$$

$$\dot{C}_q = c_q \dot{E}_q \tag{6}$$

Accordingly, for a kth component receiving heat transfer and generating power, we may write [2]

$$\sum_e (c_e \dot{E}_e)_k + c_{w,k} \dot{W}_k = c_{q,k} \dot{E}_{q,k} + \sum_i (c_i \dot{E}_i)_k + \dot{Z}_k \tag{7}$$

In the case of a single product of the plant, the unit cost of the product can be easily determined using Eq. (7). In the case of a multi-product plant such as cogeneration plants, the cost-balance equation is not sufficient. Additional criteria are required to determine the relationship between the unit costs of the different products. This is where exergy can be used as a basis for cost allocation of the products.

A diesel engine powered cogeneration (DEPC) plant (see Fig. 1) is considered as an illustrative example of the exergy

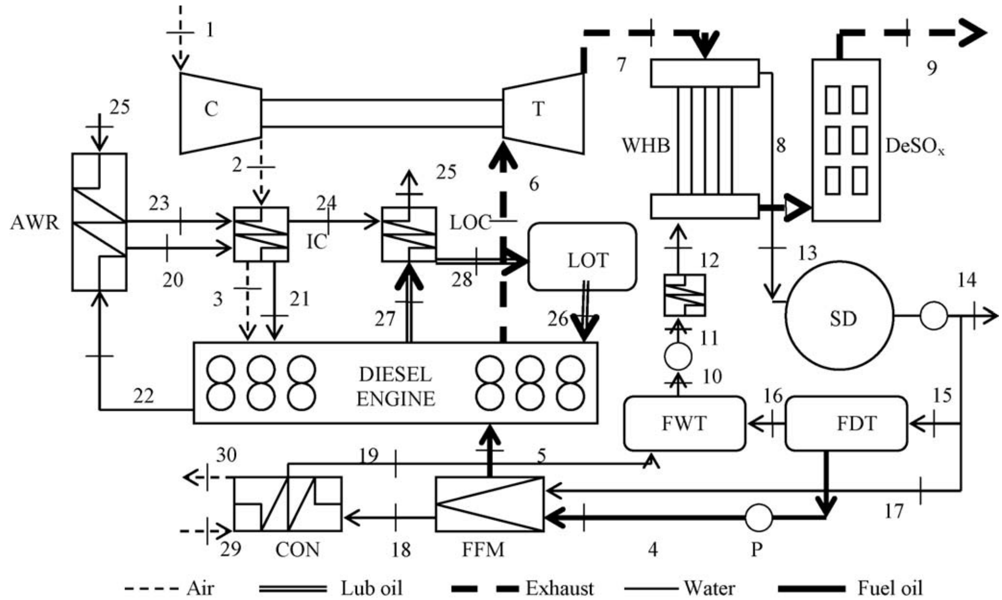

Fig. 1. The Schematic of an actual diesel engine powered cogeneration plant. C: compressor, T: turbine, WHB: waste heat boiler, DeSO$_x$: desulphurization, AWR: air–water radiator, IC: intercooler, LOC: lubrication oil cooler, LOT: lubrication oil tank, SD: steam drum, FWT: feed water tank, FDT: fuel oil day tank, CON: condenser, FFM: fuel forwarding module, and P: pump.

costing of co-generated products. When the engine starts, air is charged to the compressor of the turbocharger unit. The turbocharger consists of a turbine and a compressor, which are mounted on a common shaft. The shaft power obtained by the operation of diesel engine is transferred to the generator for electricity production. The exhaust gases leaving the engine flow through the turbine of the turbocharger unit to produce the necessary shaft work for the compressor. The air leaving the compressor is cooled by water in an intercooler before air enters the engine cylinders. The exhaust gases leaving the turbine enter the exhaust gas boiler unit to transfer heat to the feed water to produce steam for manufacturing facilities in the factory and for preheating of streams in the auxiliary equipments such as fuel forwarding module (FFM) and fuel oil in daily usage tank (FDT). The exhaust gas leaving the boiler is sent to the DeSO$_x$ (desulphurization) unit in which the SO$_x$ emission is lowered to the acceptable legal values. After the DeSO$_x$ unit, the exhaust gases are released to the atmosphere. In Table 1, exergetic cost rate balances and related auxiliary equations for each subsystem of the DEPC plant are presented [80,81].

The explicit determinations of auxiliary equations based on exergy criteria were presented in previous works [7,8,12]. These methods are known as the equality, the extraction and the by-product methods. All these methods require a judgment regarding the purpose of each unit of the plant and distribute the costs proportionally to exergy contents of the flow. These three methods are applied to the turbine of the turbocharger unit of the DEPC plant (see Fig. 1) as an illustrative example. The exergetic cost-balance equation of the turbine from Table 1 is

$$\dot{C}_6 - \dot{C}_7 + \dot{Z}_{\mathrm{TURBINE}} = \dot{C}_{\mathrm{W}_{\mathrm{TURBINE}}} \tag{8a}$$

or

$$c_6\dot{E}_6 + \dot{Z}_{\mathrm{TURBINE}} = c_7\dot{E}_7 + c_{\mathrm{W}}\dot{E}_{\mathrm{W}} \tag{8b}$$

Assuming the exergetic cost of the inlet stream c_6 is known, the cost-balance equation has two unknowns, namely, c_7 and c_{W}. Thus, an assumption must be made regarding the allocation of the cost to the two outputs: shaft power $\dot{E}_{\mathrm{W}}$ and the exit stream $\dot{E}_7$.

(i) In *the equality method*, the generation of the two products is considered to have the same priority, so the cost of high temperature exhaust gas of the turbine is charged to the production of both outputs (products) proportionally to their exergies as

$$c_7 = c_{\mathrm{W}} = \frac{c_6\dot{E}_6 + \dot{Z}_{\mathrm{TURBINE}}}{\dot{E}_7 + \dot{E}_{\mathrm{W}}} \tag{9}$$

(ii) In *the extraction method*, it is considered that the purpose of the turbine is to generate shaft power and thus the entire cost of the turbine must be charged against it. This results in assuming the unit exergetic cost of the exhaust gas entering the turbine to be the same as that of the exhaust gas leaving it. Thus,

$$c_7 = c_6 \tag{10}$$

$$c_{\mathrm{W}} = \frac{c_6(\dot{E}_6 - \dot{E}_7) + \dot{Z}_{\mathrm{TURBINE}}}{\dot{E}_{\mathrm{W}}} \tag{11}$$

(iii) In *the by-product* method, the cost of one of the outputs is assumed to be known. It is assumed that the generation of process stream is essential even if no shaft power would be generated. Therefore, the exergy of the exhaust gas is costed as if it were produced alone in a diesel engine at the required pressure and temperature. Therefore, the cost of shaft power is determined by the cost balance.

Table 1 shows the exergetic cost rate balances and corresponding auxiliary equations for each subsystem of the DEPC plant given in Fig. 1 [80,81] using the extraction method.

3.1. Exergetic cost formation process and cost accounting methodologies

3.1.1. Fuel-product model

Exergetic cost accounting provides a wide and clear vision of the usage and degradation of energy and in consequence of natural

Table 1
Exergetic cost rate balances and corresponding auxiliary equations for each subsystem of the DEPC plant. State numbers refer to Fig. 1.

Component	Exergetic cost rate balance equations for the components of DEPC	Auxiliary equations
Compressor	$\dot{C}_{W_{COMP}} + \dot{Z}_{COMP} = \dot{C}_2 - \dot{C}_1$	$\dot{C}_1 = 0 \ (\dot{E}_1 = 0)$
Intercooler	$(\dot{C}_{20} - \dot{C}_{21}) + (\dot{C}_{23} - \dot{C}_{24}) + \dot{Z}_{IC} = \dot{C}_3 - \dot{C}_2$	$\frac{\dot{C}_{21} - \dot{C}_{20}}{\dot{E}_{21} - \dot{E}_{20}} = \frac{\dot{C}_{24} - \dot{C}_{23}}{\dot{E}_{24} - \dot{E}_{23}}$
Lubrication oil cooler	$(\dot{C}_{24} - \dot{C}_{25}) + \dot{Z}_{LOC} = \dot{C}_{28} - \dot{C}_{27}$	$\frac{\dot{C}_{28}}{\dot{E}_{28}} = \frac{\dot{C}_{27}}{\dot{E}_{27}}$ $c_{24} = c_{25}$
Diesel engine	$\dot{C}_3 + \dot{C}_5 + (\dot{C}_{21} - \dot{C}_{22}) + (\dot{C}_{26} - \dot{C}_{27}) + \dot{Z}_{DE} = \dot{C}_6 + \dot{C}_{W\text{-}ELECTRIC}$	$\frac{\dot{C}_{22}}{\dot{E}_{22}} = \frac{\dot{C}_{21}}{\dot{E}_{21}}$ $\frac{\dot{C}_{26}}{\dot{E}_{26}} = \frac{\dot{C}_{27}}{\dot{E}_{27}}$
Turbine	$\dot{C}_6 - \dot{C}_7 + \dot{Z}_{TURBINE} = \dot{C}_{W_{TURBINE}}$	$c_6 = c_7$
Waste heat boiler	$(\dot{C}_7 - \dot{C}_8) + \dot{Z}_{WHB} = \dot{C}_{13} - \dot{C}_{12}$	$\frac{\dot{C}_{12}}{\dot{E}_{12}} = \frac{\dot{C}_{13}}{\dot{E}_{13}}$ $c_7 = c_8$
$DeSO_x$ unit	$(\dot{C}_9 - \dot{C}_8) + \dot{Z}_{DeSO_x} = 0$	$c_9 = 0$
Fuel oil day tank	$(\dot{C}_{15} - \dot{C}_{16}) + \dot{Z}_{FDT} = \dot{C}_4 - \dot{C}_{0,FO}$	$\frac{\dot{C}_{15}}{\dot{E}_{15}} = \frac{\dot{C}_{16}}{\dot{E}_{16}}$
Fuel forwarding module	$(\dot{C}_{17} - \dot{C}_{18}) + \dot{Z}_{FFM} = \dot{C}_5 - \dot{C}_4$	$\frac{\dot{C}_{17}}{\dot{E}_{17}} = \frac{\dot{C}_{18}}{\dot{E}_{18}} = \frac{\dot{C}_{16}}{\dot{E}_{16}}$
Condenser	$(\dot{C}_{29} - \dot{C}_{30}) + \dot{Z}_{CON} = \dot{C}_{19} - \dot{C}_{18}$	$\frac{\dot{C}_{18}}{\dot{E}_{18}} = \frac{\dot{C}_{19}}{\dot{E}_{19}}$ $c_{29} = 0$
Pump	$\dot{C}_{W_{PUMP}} + \dot{Z}_P = \dot{C}_{11} - \dot{C}_{10}$	$\frac{\dot{C}_{10}}{\dot{E}_{10}} = \frac{\dot{C}_{11}}{\dot{E}_{11}}$
DEPC	$\dot{C}_1 + \dot{C}_5 + \dot{C}_{10} + \dot{Z}_{DEPC} = \dot{C}_{14} + \dot{C}_{15} + \dot{C}_9 + \dot{C}_{W\text{-}ELECTRIC}$	$\frac{\dot{C}_{14}}{\dot{E}_{14}} = \frac{\dot{C}_{15}}{\dot{E}_{15}} = \frac{\dot{C}_{12}}{\dot{E}_{12}}$

resources [34]. Cost accounting methodologies are based on cost allocation rules. In order to identify the process of cost formation, general relationships are required that relate the overall efficiency of the plant and the cost of the products with the efficiency and the irreversibilities of each individual component that form the system [33,34,48,61].

In order to build up the cost formation in a system, productive structure information of the system must be obtained. This structure consists of a qualitative and quantitative analysis of the relations that link the flows of exergy inputs and outputs between components of an economic unit. Since all thermal plants have a defined aim to produce one or more *products*, the quantity of resources must also be identified through mass or energy flows which are known as *fuel*. Thus, each of the components of the plant can be characterized by its fuel and its product(s). In Table 2, the fuel and product exergy definitions of each component in the DEPC plant is given [82].

Table 2
Definitions of the exergies of the fuels $\dot{E}_F$ and the exergies of products $\dot{E}_P$ for the components of the DEPC plant. State numbers refer to Fig. 1 [82].

Component	$\dot{E}_F$	$\dot{E}_P$
Compressor	$\dot{E}_C$	$\dot{E}_2 - \dot{E}_1$
Intercooler	$\dot{E}_2 - \dot{E}_3$	$(\dot{E}_{21} - \dot{E}_{20}) + (\dot{E}_{24} - \dot{E}_{23})$
Lubrication oil cooler	$\dot{E}_{27} - \dot{E}_{28}$	$\dot{E}_{25} - \dot{E}_{24}$
Diesel engine	$\dot{E}_f^{ch} + \dot{E}_3 + \dot{E}_5 + \dot{E}_{21} + \dot{E}_{26}$	$\dot{E}_6 + \dot{E}_{22} + \dot{E}_{27} + \dot{E}_{31}$
Turbine	$\dot{E}_6 - \dot{E}_7$	$\dot{E}_T$
Waste heat boiler	$\dot{E}_7 - \dot{E}_8$	$\dot{E}_{13} - \dot{E}_{12}$
Fuel oil day tank	$\dot{E}_{15} - \dot{E}_{16}$	$\dot{E}_4 - \dot{E}_{0,FO}$
Fuel forwarding module	$\dot{E}_{17} - \dot{E}_{18}$	$\dot{E}_5 - \dot{E}_4$
Condenser	$\dot{E}_{18} - \dot{E}_{19}$	$\dot{E}_{30} - \dot{E}_{29}$
Pump	$\dot{E}_P$	$\dot{E}_{11} - \dot{E}_{10}$

In accordance with the *fuel-product* model, the product of one component is used as fuel for another component or as part of the total production of the plant. Thus,

$$\dot{E}_{P,i} = \dot{E}_{F,i,0} + \sum_{j=1}^{n} \dot{E}_{F,i,j} \quad i = 0, 1, \ldots, n \tag{12}$$

where $\dot{E}_{F,i,j}$ is the production portion of the ith component and is the fuel of the jth component. In Eq. (12), the component "0" is considered as the environment, and then $\dot{E}_{F,i,0}$ represents the production portion of the ith component which leads to the final product, coming from the environment to the ith component. The resources entering each component can also be expressed as

$$\dot{E}_{F,i} = \dot{E}_{F,0,i} + \sum_{j=1}^{n} \dot{E}_{F,j,i} \quad i = 0, 1, \ldots, n \tag{13}$$

where $\dot{E}_{F,0,i}$ represents the external resources entering to the plant, which enters through ith component. The total fuel and product of the system can be obtained as [34–36,39]

$$\dot{E}_{F,total} = \sum_{j=1}^{n} \dot{E}_{F,0,j} \tag{14}$$

$$\dot{E}_{P,total} = \sum_{j=1}^{n} \dot{E}_{F,j,0} \tag{15}$$

3.1.2. The cost equations of fuel-product model

The proposed fuel-product model can be applied to exergetic cost structure formation of a system and exergetic costs of product

and fuel can be expressed, respectively as

$$\dot{C}_{P,i} = \dot{C}_{F,i,0} + \sum_{j=1}^{n} \dot{C}_{F,i,j} \quad i = 0, 1, \ldots, n \tag{16}$$

$$\dot{C}_{F,i} = \dot{C}_{F,0,i} + \sum_{j=1}^{n} \dot{C}_{F,j,i} \quad i = 0, 1, \ldots, n \tag{17}$$

The proposed cost model of fuel-product approximation is the base of the "Exergetic Cost Theory" [33]. It is explained in the next section with the cost assessment rules of the theory. The exergetic cost-balance equations and auxiliary relations of the DEPC plant given in Table 1 are based on the fuel-product model and obtained by using SPECO approach that is one of the important thermoeconomic methodologies described in the next section.

4. Thermoeconomic methodologies

Following El-Sayed and Gaggioli [7,8], thermoeconomic methods can be classified in two groups: algebraic methods and calculus methods. These two basic categories are examined with their subcategories and related works.

4.1. Algebraic methods

The algebraic methods use algebraic cost-balance equations derived from conventional economic analysis and auxiliary cost equations for each subcomponent of any system presented [2]. They are related with the cost formation process of the system in order to investigate the average costs.

4.1.1. The theory of the exergetic cost (TEC)

Theory was developed by Lozano and Valero [33] and the methodology presented in theory is based on a set of propositions [2]. This theory permits the introduction of a new thermodynamic concept called exergy cost. For given a system whose limits, disaggregation level, and production aim of the subsystems have been defined, exergy cost E^* of a physical flow is defined as the amount of exergy needed to produce this flow [33]. The first step in the application of this methodology is the division of the system into units, which may adapt to a component or a set of components. A single *product* and *fuel* for each component in the system must be defined. Thus, a system of equations can be built with a cost-balance equation for each unit (proposition 1), cost allocation equations for external flows into the system for which costs are externally defined (proposition 2), and losses for which the cost is set equal to zero (proposition 3). However, this procedure is rarely enough. The solution may be possible when two following propositions are considered: (1) if definition of *fuel* of a component includes a stream that goes through another component and is used in it, then the unit cost of the stream flowing into and out of the component is the same (proposition 4a). (2) If the *product* of a component is composed of two or more streams then the unit cost of those streams are equal (proposition 4b). Using the *F (fuel)-P (product)-L (loss)* definitions, corresponding matrices can be developed. Starting from these matrices and using the data from design and operation of the any thermal power plant, it is possible to carry out the exergetic and energetic analysis of the plant. The unit exergetic costs obtained from the procedure can be used for the optimization of any thermal plant. This methodology is straightforward in its application, allowing for improvements and modifications.

4.1.2. The theory of exergetic cost—disaggregating methodology (TECD)

This theory was proposed by Valero and Lozano [33,34] searching the thermoeconomic unification methodology which is similar to Frangopoulos' *Thermoeconomical Functional Analysis* (*TFA*) [22–25]. The exergetic cost determined is distributed among all other components according to the variation of entropy within each one.

4.1.3. Exergoeconomic analysis (EEA) methods

The exergoeconomics approach was proposed by Tsatsaronis and co-workers [1–4,35–37,52]. There are two possible variants in these methodologies: *specific cost* and *average cost*. The average cost concept is very similar to the application of *Theory of the Exergetic Cost*. In the *specific-cost* method, the cost of the addition of exergy to a material/stream current is determined and charged to the unit that makes use of that exergy. This means that a component will obtain the exergy from a stream at different costs, depending on the components that supplied the exergy to that stream. Due to the purpose of the energy conversion plant (i.e. power plant or combined heat and production plant) the division between subcomponents of the main plant may be made. If power produced is the primary product, cost of all external irreversibilities is loaded on the electricity. If heat is produced as primary one, the similar procedure is followed by the steam produced in the plant. The optimization procedure of the exergoeconomics is based on an iterative design improvement procedure that does not aim at calculating the global optimum of a predefined objective function [35], as the conventional optimization methods perform, but tries to find a good solution for the overall system design. The methods involve some characteristic parameters of exergoeconomic analysis such as relative cost difference, exergoeconomic factor, and exergetic efficiency. These methods can be grouped in three classes: (i) Last-in-First-out (LIFO) principle, (ii) Specific Exergy Costing/Average Cost (SPECO/AVCO) approach, and (iii) Modified Productive Structure Analysis (MOPSA) approach.

Last-in-First-out (*LIFO*) *principle*. This approach was developed by Tsatsaronis et al. [1]. LIFO principle of cost accounting is used for the spent exergy units to calculate the cost of exergy supply to the carrier. The method eliminates the need for auxiliary assumptions in the exergoeconomic analysis of energy systems and improves the fairness of the costing process. This approach is based on a simple idea, which is directly linked between asset management and valuation method: The exergy units that are supplied last to the material stream are used first. Thus, it is straightforward to calculate the cost associated with the exergy units removed from a material stream in a process step provided that this cost is calculated in the previous steps during which the exergy units currently removed from the stream are then supplied to it.

Specific Exergy Costing/Average Cost (*SPECO/AVCO*) *Approach*. This method was first presented by Lazzaretto and Tsatsaronis [48,52]. Following improvements of the methodology by Tsatsaronis and co-workers it includes combination with fuzzy inference systems for a more exact exergoeconomic evaluation of plant components [54] and systematic improvement of SPECO methodology [71]. According to the approach, fuels and products are defined systematically by registering exergy additions to and removals from each material and energy stream. The records of cost additions to and removals from the same stream in conjunction with the application of the LIFO principle are then used to calculate local average costs. This method consists of three main steps: (1) identification of exergy streams, (2) definition of fuel and product for each system component, and (3) cost-balance equations. This method has been largely and successfully used and applied to thermal systems by the researchers in the area of thermoeconomics [4,67,71–81].

Modified Productive Structure Analysis (*MOPSA*) *approach*. This approach was first presented by Kim et al. [45]. The method is based on the exergy costing approach without flow-stream cost calculations. Lozano and Valero [33] presented the cost evaluation

technique of the thermal system, which provided a theoretical basis for the exergy costing method. In the MOPSA method, a cost-balance equation is obtained by assigning a unit exergy cost to each disaggregated exergy in the stream at any state. The monetary evaluations of various exergy costs, as well as the production cost of electricity for the thermal system, are obtained by solving the set of equations for the unit of exergoeconomic costs. This method has been applied and compared with SPECO approach for the exergoeconomic analysis and optimization of combined heat and power plants [45–57,60].

4.2. Calculus methods

Calculus methods are built on differential equations. Cost flows in a system are developed in a link between optimization procedures that are based on the Lagrange multipliers and they are used to determine marginal costs. The characteristic difficulty in the application of calculus methods to complex systems such as combined heat and power plants is the fact that the Lagrange multipliers vary from iteration to iteration when component thermoeconomic isolation is not achieved [6]. Following approaches are used in calculus methods.

4.2.1. Thermoeconomic functional approach (TFA)

This approach was first studied as a Ph.D. thesis by Frangopoulos [22–27] while the first remarkable application of it was the CGAM problem [38]. This methodology is based on the Lagrangian method of mathematical optimization. Its complete implementation requires the existence of a sufficiently accurate simulation of the system in order to determine the first order derivatives of the objective function. The method is based on the decomposition of the system into subcomponents, which may or may not correspond to a physical component of the system. Each component has a single product, and costs can be determined by the solution of the cost balances of the system components. The TFA optimization is based on the direct use of an (usually nonlinear) optimization algorithm since it requires the least effort in the analysis of complex systems. The method introduces the functional diagram concept and assigns only one function and one product to each component so that auxiliary equations are not needed in the solution procedure. This method does not give any information about the physical and economic interrelationships among the system components. On the other hand, scaling of the variables and of the objective function is required to achieve convergence to the optimum point. Discrepancies that exist in searching convergence to the global optimum can be solved by searching different initial points in the problem. In order to find the optimum solution of more complex systems, Frangopoulos formulated *Intelligent Functional Approach* (*IFA*) which was a further development of the TFA [24,25].

4.2.2. Engineering functional analysis (EFA)

The basics of the EFA theory were developed by von Spakovsky and Evans [30]. The first laborious work of the method was the CGAM problem [39]. The basic decomposition algorithm of the EFA method is the variation on the algorithm proposed by Frangopoulos [22,23]. It is based on a multi-dimensional version of Modified Regula-Falsi Method [83]. In the EFA approach, any thermoeconomic model exists on two levels: as a system basis model and as a set of detailed subgroup models [39]. These two models include information on the internal geometry and material composition of each subgroup. The extent to which these individual subgroup optimums are consistent with the global system optimum depends on how well the isolation of the subgroups is established by the optimization of the system basis model. The optimization procedures of two interrelated models mentioned is possible with a certain number of iterations which occur in the link between the models and internal economy of the system presented. The decomposition strategy used in calculus methods in thermoeconomics is based on the *Principle of Thermoeconomic Isolation* by Evans [6]. The idea is stated as follows: A component of a thermal system is thermoeconomically isolated from the rest of the system if its production P_i and the unit cost of the resources λ_i are known quantities and independent from the rest of the component variables. Decomposition may only approach the global optimum because of the degree of thermoeconomic isolation of the independent variables, the choice of subgroups and their functions, and the nature of dependent variables [83].

4.2.3. The structural theory of thermoeconomics (STT)

This was proposed as a standard and common mathematical formulation for all thermoeconomic methodologies employing thermoeconomic models that can be expressed by linear equations [34]. The Theory of Exergy Cost (TEC), the SPECO/AVCO approach and the Thermoeconomic Functional Analysis (TFA) can be dealt with the structural theory. The Last-in-First-Out (LIFO) approach can also be reproduced with the structural theory.

5. Comparison of the thermoeconomic methodologies on the CGAM problem

The CGAM problem was constructed to examine the optimum design parameters of a simple combined heat and power plant which produces 30 MW electricity and 14 kg/s of saturated steam at 20 bars [36]. The two optimization criteria were the maximization of exergetic efficiency and the minimization of the total cost rate of the plant. The installation of the plant consists of a gas turbine followed by an air preheater which uses part of thermal energy of the gases leaving the turbine, and a heat-recovery steam generator in which the required steam is produced (see Fig. 2) [2,36,53]. The base case design data of CGAM problem is given in Table 3 [2,36–39,53].

In the definition of CGAM problem, three models were considered: the physical model which describes the behavior of the system; the thermodynamic model which describes the equations of state used to calculate the thermodynamic properties; and the economic model which describes the equations for calculating the capital costs of the components. In order to simplify these models, the following assumptions were made: (i) the air and the combustion gases behave as ideal gases with constant specific heats, (ii) for combustion calculations, the fuel is taken to be methane CH_4, and (iii) all components except the combustion chamber are adiabatic.

5.1. Conventional approach

In the first study of the CGAM problem [36], physical, thermodynamic and economic models were described in detail for each component of the plant (see Fig. 2). In this primary study, the optimization problem was expressed as the minimization of the total cost flow rate of the plant $\dot{C}_T$, subject to the constraints imposed by the physical, thermodynamic, and cost models of the installation. That is,

$$\dot{C}_T = c_f \dot{m}_f LHV + \dot{Z}_C + \dot{Z}_{AP} + \dot{Z}_{CC} + \dot{Z}_T + \dot{Z}_{HRSG} \tag{18}$$

where c_f is the cost per unit energy of the fuel for the total plant, $\dot{m}_f$ is the mass flow rate of the fuel, *LHV* is the lower heating value of the fuel, and $\dot{Z}_k$ is the total capital cost associated with the subcomponents of the plant, i.e., compressor, air preheater, combustion chamber, turbine and heat recovery steam generator. This first solution of the CGAM problem was obtained through conventional optimization techniques. The decision variables of the CGAM problem were the compressor pressure ratio P_2/P_1, isentropic compressor efficiency η_{sc}, isentropic turbine efficiency

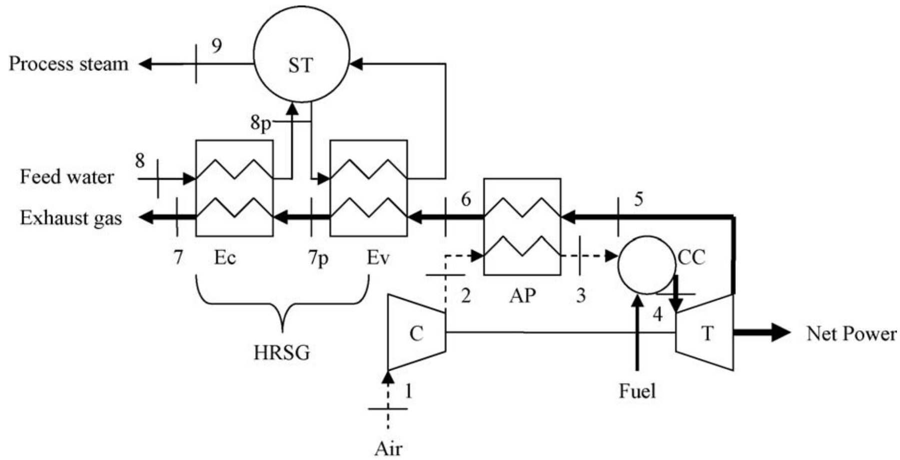

Fig. 2. The flow schematic of the CGAM problem. C: compressor, AP: air preheater, CC: combustion chamber, T: turbine, Ev: evaporator, Ec: economizer, ST: steam tank, HRSG: heat recovery steam generator.

η_{st}, temperature of the air entering the combustion chamber T_3, and temperature of the combustion products entering the turbine T_4. All other thermodynamic variables were calculated as functions of the decision variables. The mathematically optimal solution results of this introductory study [36] are given in Table 4.

5.2. Exergoeconomic methodology approach

In the second study of the sequential CGAM problem papers [37], exergoeconomic techniques were applied and discussed for design optimization. The exergoeconomic evaluation of the system considered (see Fig. 2) consists of a detailed exergy analysis, an economic analysis conducted at the component level, calculation of the cost of each stream using an appropriate exergy costing method [31], and a final evaluation at the component level conducted with the aid of some relevant exergoeconomic variables [2]. The exergy analysis was performed to identify the sources of the thermodynamic inefficiencies and to facilitate development of design changes to improve the overall system efficiency. Thus, the exergy destruction in a component can be calculated from the exergy balance as

$$\dot{E}_D = \sum \dot{E}_{i,in}^{TOT} - \sum \dot{E}_{i,out}^{TOT} \tag{19}$$

where $\dot{E}_i^{TOT}$ is the flow rate of total exergy associated with the ith material or energy stream at the inlet (for subscript *in*) and outlet (for subscript *out*) of the component. The exergy values of fuel and product for the kth plant component, exergy destruction may be written as

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k} - \dot{E}_{L,k} \tag{20}$$

where $\dot{E}_{L,k}$ represents the exergy loss in the kth component. In these papers, the performance of an energy system from the thermodynamic point of view was evaluated in addition to the exergy destruction, the exergetic efficiency, and two exergy destruction ratios [2,31,37]. The exergetic efficiency is the ratio of product exergy to the fuel exergy:

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \tag{21}$$

In addition to the exergy destruction $\dot{E}_{D,k}$ and the exergetic efficiencies ε_k, the exergy destruction ratio $y_{D,k}$ is used in the thermodynamic evaluation of a component. This ratio compares the exergy destruction in the kth component with the total fuel exergy supplied $\dot{E}_{F,total}$ to the overall system:

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,total}} \tag{22}$$

Alternatively, the exergy destruction rate of the kth component can be compared to the total exergy destruction rate $\dot{E}_{D,total}$:

$$y_{D,k}^{*} = \frac{\dot{E}_{D,k}}{\dot{E}_{D,total}} \tag{23}$$

The exergy loss ratio is defined similarly to Eq. (22), by comparing the exergy loss to the total fuel exergy supplied to the overall system

$$y_{L,total} = \frac{\dot{E}_{L,total}}{\dot{E}_{F,total}} \tag{24}$$

Table 3
Base case design data of the CGAM problem [2,36–39,53].

State	Substance	Mass flow rate (kg/s)	Temperature (K)	Pressure (bar)
1	Air	91.2757	298.150	1.013
2	Air	91.2757	603.738	10.130
3	Air	91.2757	850.000	9.623
4	Exhaust gas	92.9176	1520.00	9.142
5	Exhaust gas	92.9176	1006.162	1.099
6	Exhaust gas	92.9176	779.784	1.066
7	Exhaust gas	92.9176	426.897	1.013
8	Water	14.0000	298.150	20.000
9	Water	14.0000	485.570	20.000
10	Fuel (methane)	1.6419	298.150	12.000

Table 4
Optimum values of the decision variables and costs in the CGAM problem through mathematical optimization method [36].

Decision variables	Optimum values
P_2/P_1	8.5234
η_{sc}	0.8468
η_{st}	0.8786
T_3 (K)	914.28
T_4 (K)	1492.63
Total cost rate ($/s)	0.362009
Fuel cost rate ($/s)	0.325489
Investment cost rate ($/s)	0.036520
Cost of combustion chamber ($)	0.1469×10^6
Cost of air compressor ($)	0.1348×10^7
Cost of gas turbine ($)	0.1927×10^7
Cost of air preheater ($)	0.8277×10^6
Cost of HRSG ($)	0.1202×10^7

Table 5
Comparison of the global optimum values of decision variables and costs with the two workable design condition optimal values in the CGAM problem through exergoeconomic analysis and optimization methodology [37].

Decision variables	Optimum case		Case 14 [37]		Case 22 [37]	
P_2/P_1	8.52		10.0		8.0	
η_{sc}	0.847		0.850		0.850	
η_{st}	0.879		0.875		0.870	
T_3 (K)	914.3		900.0		933.0	
T_4 (K)	1492.6		1485.0		1500.0	
Component	Δr (%)	$\Delta\varepsilon$ (%)	Δr (%)	$\Delta\varepsilon$ (%)	Δr (%)	$\Delta\varepsilon$ (%)
Air compressor	4.08	1.30	9.04	1.82	4.18	1.31
Air preheater	22.03	−5.64	12.73	−4.27	25.28	−5.93
Gas turbine	4.56	0.87	1.35	0.50	2.88	0.73
HRSG	36.71	−15.26	38.07	−15.58	37.02	−15.30
$\dot{D}_{L,tot}$ ($/h)	46.70		47.4		49.4	
$\dot{D}_{L,tot}^{OPT}$ ($/h)	26.70		26.8		27.2	
Estimated value of the objective function ($/h)	1302.8		1307.9		1307.6	
Calculated value of the objective function ($/h)	1303.4		1308.8		1305.3	

The detailed economic analysis of the CGAM problem presented in the second study [37] was conducted at the component level as part of the exergoeconomic evaluation and simplified by assuming some economic factors such as capital recovery factor (β), annual system operation time at the nominal capacity (τ) to specific numerical values. Since the exact formulations of the cost balances and additional auxiliary equations depend on the exergy costing method applied (see Eqs. (1) through (7)) and on the types of exergy values (i.e., total, chemical, physical, thermal, and mechanical exergy), two separate exergy costing methods were applied [37]. These methods were the traditional average-cost exergy costing method (AVCO) [7,8] and the specific-cost exergy costing method (SPECO) [48,52]. AVCO method was the simplest method applied to CGAM problem among the others. The SPECO method was based on a detailed accounting of the cost at which every exergy addition to a material stream occurs. Thus in a process during which exergy was removed from a stream, the cost at which the removed exergy had been previously supplied to the stream was calculated and was charged to the product of the process [48,52,54,71]. These two methods were applied to the problem combined with (i) physical and chemical exergy values and (ii) thermal, mechanical and chemical exergy values. In this paper, two major exergoeconomic variables were defined for the first time: the relative cost difference factor (Δr) and the exergoeconomic factor (f) which would be very useful parameters in the evaluation of exergoeconomic analysis and optimization of thermal systems later [37,45,46,51,52,54,60,73,77,80,81]. The relative cost difference r_k for the kth component is defined as

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{25}$$

In an iterative cost optimization of a system, if the cost of fuel of a major component changes from one iteration to the next, the objective of the cost optimization of the component should be to minimize the relative cost difference instead of minimizing the cost per exergy unit of the product with this component [2]. In evaluating the performance of a component, we want to know the relative significance of each category. This is provided by the exergoeconomic factor f_k defined for the kth component as

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k}(\dot{E}_{D,k} + \dot{E}_{L,k})} \tag{26}$$

The total cost rate causing the increase in the unit cost from fuel to product is given by the denominator in Eq. (26). Accordingly, the exergoeconomic factor expresses as a ratio the contribution of the non-exergy related cost to total cost increase. A low value of the exergoeconomic factor calculated for a major component suggests that cost savings in the entire system might be achieved by improving the component efficiency (reducing the exergy destruction) even if the capital investment for this component will increase. On the other hand, a high value of this factor suggests a decrease in the investment costs of this component at the expense of its exergetic efficiency [2]. Three optimal cases were compared: global optimum case of the CGAM problem and two different initial workable design case optimal solutions, namely cases 14 and 22 [37]. Comparison of the results for these three cases is given in Table 5. The exergoeconomic analysis and optimization technique developed and applied to CGAM problem in the second study of the sequential papers show that the method is a valuable tool in the exergoeconomic analysis of the complex existing thermal systems and it has been applied to different thermal systems in the numerous papers [1,4,31,33,37,45,46,51,52,54,60,73,77,80,81] since it was published.

5.3. Thermoeconomical functional analysis approach (TFA)

The application of the thermoeconomical functional approach (TFA) to the CGAM problem was first studied by Frangopoulos [38]. He applied three different analysis and optimization procedures in his study: (i) direct use of a nonlinear programming algorithm, (ii) thermoeconomic functional approach, and (iii) modular simulation and optimization of the system. In the direct application of the nonlinear programming method, the objective of the optimization was defined as the minimization of the total cost rate (i.e. capital and operation expenses) of the system

$$\min F = \sum_{r=1}^{n} \dot{Z}_r + c_f \dot{m}_f LHV_u \tag{27}$$

where $\dot{Z}_r$ represents amortized capital cost rate of component r, including fixed charges and maintenance. A specific computer program was used for the numerical solution of the optimization problem consisting of the main program, double precision function, constraints subroutine and the optimization algorithm developed by Frangopoulos himself. In the statement of the functional optimization problem, the same objective function (Eq. (27)) was used. In the two methods, the same independent variables were taken into account as in the previous applications of conventional optimization method [36] and exergoeconomic optimization [37]. In the solution of the functional optimization problem, Lagrange multipliers were used. The simplified form of the Lagrangian was defined for the CGAM problem as [38]

$$L = \sum_{r=1}^{6} (\Gamma_r - \lambda_r y_r) + (\Gamma_{0.2} - \lambda_{0.2} y_{0.2}) + \lambda_3 \hat{y}_{3.0} + \lambda_5 \hat{y}_{5.0} \tag{28}$$

where

$$\Gamma_r = Z_r + \sum_{r'}^{6} \lambda_{r',r} Y_{r',r}, \quad r = 1, 2, \ldots, 6 \tag{29}$$

The required conditions

$$\nabla_x L(x, y, \lambda) = 0, \quad \nabla_y L(x, y, \lambda) = 0, \quad \nabla_\lambda L(x, y, \lambda) = 0 \tag{30}$$

were imposed on the Lagrangian to obtain the equations

$$\frac{\partial}{\partial x} \sum_{r=1}^{6} \Gamma_r = 0 \tag{31}$$

$$\lambda_{0.2} = \frac{\partial \Gamma_{0.2}}{\partial y_{0.2}} = c_f \tag{32}$$

$$\lambda_r = \frac{\partial \Gamma_r}{\partial y_r} \tag{33}$$

$$\lambda_{r',r} = \lambda_r \tag{34}$$

In the solution of the nonlinear system presented for the CGAM problem, numerical methods were used and the minimization of Lagrangian (Eq. (28)) with respect to x by means of a nonlinear programming algorithm that was found to be more efficient than the analytic derivatives (by avoiding infeasible points) procedure [38]. The modular approach to the CGAM problem was given for demonstration purpose in the paper since the system presented through the problem is not very complex and detailed design characteristics are not necessary. The comparable optimization results for the nominal values of parameters in terms of three methods presented [38] are given in Table 6.

Among three methodologies applied by Frangopoulos in his paper as part of sequential studies of the CGAM problem in the same issue, the direct use of nonlinear algorithm was the simplest one because it required the least effort in system analysis, but it did not include any information about the internal economy of the system (i.e. physical and economic relationships among the subcomponents of the CGAM system) [38]. The CGAM problem was solved by TFA successfully since the distribution of functions developed for subcomponents of the system established interrelations between components or between system and the environment leading to a functional diagram of the system [22,23]. However the capabilities of TFA and IFA which was a further development of TFA are better revealed in more complicated situations than CGAM problem, when the solution of the complete optimization problem is required [22–25,38]. The modular approach has some significant advantages when detailed design of components is required. This methodology can be combined with direct nonlinear algorithms and TFA or IFA method; in particular decomposition of the optimization problem is applied. In Frangopoulos paper for CGAM problem, this was not the case, and therefore modular approach was applied to the problem only with demonstrative purposes.

Table 6
Comparison of the nominal values of the decision variables and total cost of the plant for the CGAM problem through direct use of the nonlinear programming method, thermoeconomical functional approach and modular approach [38].

Decision variables	Method		
	Direct use of the nonlinear algorithm [38]	TFA	Modular approach
P_2/P_1	8.59730	8.59770	8.59050
η_{sc}	0.84641	0.84650	0.84653
η_{st}	0.87886	0.87871	0.87878
T_3 (K)	912.77	913.14	912.93
T_4 (K)	1491.40	1491.97	1491.50
F ($/year)	1.0426×10^7	1.0426×10^7	1.0426×10^7

5.4. Engineering functional analysis approach (EFA)

von Spakovsky constructed a thermoeconomic structure for the CGAM problem by applying engineering functional analysis method (EFA) [39]. Methodology in his paper consisted of two distinct parts: an economic model which represents the thermodynamic and economic behavior of the system and an algorithm to solve the model for optimum. The general form of objective function for CGAM problem in this paper was defined as [39]

$$\text{minimize } \dot{\Gamma}^{\$}_{total} = \dot{C}^{\$}_{C} + \dot{C}^{\$}_{APH} + \dot{C}^{\$}_{CC} + \dot{C}^{\$}_{T} + \dot{C}^{\$}_{HRSG} + \dot{\Gamma}^{\$}_{fuel} + \dot{K}^{\$} \tag{35}$$

with respect to

$$x = \{x_i\} = \{x_c\}, \quad i = 1, 2, \ldots, I \text{ and } c = C, APH, CC, T, HRSG \tag{36}$$

subject to system products, component inputs, junctions, branches, and physical limits respectively as

$$h_{Pj} = Y_j - Y_j(x_{Pj}) = 0, \quad j = 1, 2 \ldots, P \tag{37}$$

$$h_c = Y_j - Y_j(x_c, Y_c) = 0, \quad j = P+1 \ldots, C \text{ and } c = C, APH, CC, T, HRSG \tag{38}$$

$$h_{Jm} = Y_{Jm} - \sum_{in=1}^{2} Y_{j+in} = 0, \quad j = C+1 \ldots, L \text{ and } m = 1 \ldots, L \tag{39}$$

$$h_{Bn} = \sum_{out=1}^{2} Y_{Bnout} - Y_j = 0, \quad j = L+1 \ldots, B \text{ and } n = 1 \ldots, B \tag{40}$$

$$g_k(x, y) \geq 0, \quad k = 1 \ldots, K \tag{41}$$

where

$$\dot{C}^{\$}_{c} = C^{\$}_{c}(x_c, Y_c), \quad c = C, APH, CC, T, HRSG \tag{42}$$

$$\dot{\Gamma}^{\$}_{fuel} = \Gamma^{\$}_{fuel}(x_{CC}, Y_{CC}) \tag{43}$$

Each of the general mathematical functions defined in Eqs. (35) through (43) were derived based on the equations given in the introductory paper of CGAM problem series [36,39]. The internal economy of the system was determined by EFA using Lagrange's method of undetermined multipliers since with this approach, the real unit or marginal costs associated with developed thermoeconomic structure and model in the paper were calculated. Thus Lagrangian was constructed from the objective function and equality constraints such that [39]

$$\begin{aligned}\dot{L}_{total} = {} & \sum_{c=1}^{n} \dot{C}^{\$}_{c} + \dot{\Gamma}^{\$}_{fuel} - \sum_{j=1}^{P} \lambda_j [Y_j - Y_j(x_{P_j})] - \sum_{j=P+1}^{n} \lambda_j [Y_j \\ & - Y_j(x_c, Y_c)] - \sum_{j=n+1, m=1}^{L} \lambda_j \left(Y_{J_m} - \sum_{in=1}^{2} Y_{j+in} \right) \\ & - \sum_{j=L+1, n=1}^{B} \lambda_j \left(\sum_{out=1}^{2} Y_{B_{nout}} - Y_j \right)\end{aligned} \tag{44}$$

The methods used in the optimization process in terms of EFA method were categorized in the paper as: modular, the Lagrangian and decomposition approaches. For decomposition approaches, two different sets of subgroups were designated namely Case 1 and Case 2 [39]. In Case 1, the first set of subgroups divided the system into two subgroups: the air compressor as one and the remaining

Table 7
Optimum values of the objective function, component and fuel costs and the decision variable set for different methodologies of optimization through EFA [39].

Design variables	Modular approach	Lagrangian approach	Decomposition approach (Case 1)	Decomposition approach (Case 2)
P_2/P_1	8.59822	8.59859	8.49996	8.49996
η_{sc}	0.84678	0.84675	0.84991	0.84991
η_{st}	912.601	912.281	924.764	900.09
T_3 (K)	0.87874	0.87900	0.88000	0.87991
T_4 (K)	1491.566	1491.440	1528.970	1480.153
$\dot{\Gamma}^{\$}_{total}$ (\$/s)	0.36204	0.36204	0.36850	0.36336
$\dot{C}^{\$}_{total}$ (\$/s)	0.03653	0.03658	0.04740	0.03467
$\dot{\Gamma}^{\$}_{fuel}$ (\$/s)	0.32552	0.32546	0.32110	0.32869

components as the other

$$x_{sub1} = \left\{ \frac{P_2}{P_1}, \eta_{I_C} \right\} \quad \text{and} \quad x_{sub2} = \{T_3, T_4, \eta_{I_T}\} \tag{45}$$

In Case 2, the second set of subgroups divided the system into four groups: the air compressor as one, the air preheater, economizer and evaporator as another, the combustion chamber as third and the gas turbine as fourth. Its decision sets were

$$x_{sub1} = \left\{ \frac{P_2}{P_1}, \eta_{I_C} \right\}, \quad x_{sub2} = \{T_3\}, \quad x_{sub3} = \{T_4\}, \quad x_{sub4} = \{\eta_{I_T}\} \tag{46}$$

A comparison of some of the major results obtained with each approach in terms of EFA method is given in Table 7. Optimum results for modular and Lagrangian were obtained as almost identical because these two methods coincided at the optimum (see Table 7) [39]. The decomposition approaches for both cases had some significant differences. This was expected since the decision variables sets defined for each subgroup were not disjoint. In Case 1, more realistic results were obtained compared with Case 2 although four subgroups decomposition solution would be expected better than two subgroups solution. The analysis and optimization methodologies applied through this paper showed that EFA methodology is a very general one and therefore very useful when applied to the modeling, optimization and analysis of energy systems either time dependent or not [39].

5.5. Exergetic cost theory (ECT or TEC) approach

Exergetic cost theory (ECT) [33] formulation of the optimization problem for CGAM system was based on the use of Lagrange multipliers [40]. The optimization problem, using the structural information provided for CGAM problem in the paper was formulated in a compact form as

$$\text{minimize } \Pi = {}^t c_e F + {}^t u Z \tag{47}$$

subject to constraints

$$K_D P = F(\mathrm{I}), \quad P_s + \langle PF \rangle F = P(\mathrm{II}), \quad P_s = \mathrm{datum(III)} \tag{48}$$

$$k = f_k(\tau), \quad r = f_r(\tau), \quad \omega = f_\omega(\tau) \tag{49}$$

where Π is the total cost of the plant product, c_e is a vector which contains the unit price of the resources entering the plant; F_e and P_s are the vectors containing the exergy of the entering resources and of the products leaving the plant respectively; u is a unit vector; Z is the vector containing the cost of the operating and maintenance of each component; K_D is a diagonal matrix containing the unit exergy consumption of each subsystem; P and F are vectors containing the exergy of the product and of exergy resources consumed (fuel) of each component; and $\langle PF \rangle$ is a matrix which defines the productive interconnection of the components [33,40].

Table 8
Optimization results for decision variables and costs in the CGAM problem by ECT methodology [40].

Decision variables	Optimum values
P_2/P_1	8.5234
η_{sc}	0.8468
η_{st}	0.8786
T_3 (K)	914.28
T_4 (K)	1492.63
Total cost rate (\$/s)	0.36201
Fuel cost rate (\$/s)	0.32549
Investment cost rate (\$/s)	0.03652
Cost of combustion chamber (\$)	0.1469×10^6
Cost of air compressor (\$)	0.1348×10^7
Cost of gas turbine (\$)	0.1927×10^7
Cost of air preheater (\$)	0.8277×10^6
Cost of HRSG (\$)	0.1202×10^7

The optimization problem with constraints was transformed into one without constraints as

$$\text{minimize } L(X, \lambda) = \Pi(X) + \sum \lambda_j G_j(X) \tag{50}$$

where Π is the original objective function of the CGAM problem, X is a vector containing the variables of the problem and λ_j is the Lagrange multiplier associated with the constraint G_j. It was demonstrated in the paper that Lagrange multipliers associated with the constraints had a profound economic significance [40]. Optimization results of the CGAM problem by ECT is given in Table 8 [40].

The structural information obtained at the optimum through the ECT method is very useful when carrying out a thermoeconomic analysis of the plant. Since CGAM problem is not a complex type of problem, the structural information developed through the analysis and optimization can be inferred from conventional thermodynamic analysis. In complex energy systems it would be very difficult [40].

5.6. Modified productive structure analysis (MOPSA) approach

Kim et al. [45] proposed and applied a thermoeconomic method called modified productive structure analysis (MOPSA) to the CGAM system and emphasized how the cost structure of the cogeneration system was affected by the chosen level of aggregation which specifies the subsystems. Kwak et al. [60] investigated the cost structure of this predefined cogeneration system with the method proposed by Kim et al. [45] and he rewrote the exergy balance equations by reflecting the exergy losses due to heat transfer. Thus, assigning a unit exergy cost to every decomposed exergy stream in the cogeneration system, non-adiabatic exergetic cost-balance equations were written as [60]

$$\begin{aligned} &\dot{E}_x^{CHE} C_0 + \left(\sum_{in\,put} \dot{E}_{x,i}^{BQ} - \sum_{out\,put} \dot{E}_{x,j}^{BQ} \right) C_{BQ} + \left(\sum_{inlet} \dot{E}_{x,i}^{T} - \sum_{outlet} \dot{E}_{x,j}^{T} \right) C_T \\ &\quad + \left(\sum_{inlet} \dot{E}_{x,i}^{P} - \sum_{outlet} \dot{E}_{x,j}^{P} \right) C_P + T_0 \left(\sum_{inlet} \dot{S}_i - \sum_{outlet} \dot{S}_j + \frac{\dot{Q}_{cv}}{T_0} \right) C_s \\ &\quad + \dot{Z}_k = \dot{E}^W C_W \end{aligned} \tag{51}$$

The exergetic cost-balance equation given in Eq. (51) yields the productive structure of the thermal system [45,51] that was developed by Lozano and Valero [33]. Kwak et al. [60] described three levels of aggregation cases in their paper. In the first case (Case I) which was the simplest one, there was no internal parameter to predict the unit cost of products, and it yielded the lowest unit cost of electricity and the highest unit cost of steam. The second case (Case II) was the next simplest one. However, in this case there was only

Table 9
The unit costs and the cost flow rates of the electricity and steam of the CGAM system by applying MOPSA approach in three different levels of aggregation cases [60].

Cost structure	Case I	Case II	Case III
Unit cost of electricity ($/GJ)	8.12	8.58	8.46
Cost flow rate ($/h)	(879.96)	(926.64)	(913.68)
Unit cost of steam ($/GJ)	11.62	10.55	10.83
Cost flow rate ($/h)	(533.24)	(484.14)	(496.99)

one internal parameter, the unit cost of negentropy (i.e., negative entropy which is defined as the entropy that the system exports to maintain its own entropy level low), and with this level of aggregation case the highest unit cost of electricity and the lowest unit cost of steam were obtained. Case III represented the highest level of disaggregation. It had three internal parameters; the unit costs of thermal and mechanical exergy and negentropy. This yielded average results between Case I and Case II. In Table 9, comparative results of three aggregation levels for the CGAM problem are given. The production costs for the CGAM listed in Table 9 satisfies the following overall cost-balance equation for the system. Note that the unit cost of electricity and steam cannot be evaluated from this equation [45,51,60].

$$\dot{E}_x^{CHE} C_0 + \dot{E}_x^{P} C_M + \sum \dot{Z}_k = \dot{W}_{net} C_W + |\dot{E}_x^{BQ}| C_{BQ} \tag{52}$$

Table 10
Comparison of exergy costing methodologies for the most disaggregated CGAM system in terms of the unit costs of electricity and steam.

Methodology	SPECO [37]	Structural theory (STT) [34]	MOPSA (Case III) [60]	Exergetic cost theory (ECT) [33]
Unit cost of electricity ($/GJ)	7.80	7.42	8.46	7.55
Cost flow rate ($/h)	(842.40)	(801.36)	(913.68)	(815.18)
Unit cost of steam ($/GJ)	10.45	10.97	10.83	10.64
Cost flow rate ($/h)	(479.60)	(503.46)	(496.99)	(488.06)

In Table 10, various exergy costing methodologies for the most disaggregated CGAM system are compared in terms of unit costs of electricity and steam. The unit costs of products of CGAM system obtained from exergetic cost theory (ECT) and SPECO approach [33,37] were close to the values of the simplest aggregation level (Case I).

As it was confirmed in related works [33,34,37,51,60], the unit cost of products is dependent on the level of aggregation of the system when the irreversibility occurred in subsystems is given explicitly in the cost-balance equations. This situation suggests that the cost structure of the system is mostly affected by the irreversibility represented by the entropy production rate at each component, and that cost structure of the system is interrelated by the irreversibility occurred at each component [60].

Table 11
Some major works on the thermoeconomic analysis and optimization of combined heat and power production systems.

Author(s)	Thermoeconomic methodology	Type of system
Tsatsaronis et al. [1]	LIFO	Simple gas turbine cogeneration
Tsatsaronis and Ho-Park [4]	SPECO/AVCO	Simple gas turbine cogeneration
Frangopoulos [22]	TFA	Complex thermal system
Frangopoulos [23]	TFA	Steam cycle cogeneration
Frangopoulos [24,25]	IFA	Steam cycle cogeneration
Frangopoulos [26,27]	TFA and optimization	Steam cycle cogeneration
von Spakovsky and Curti [29]	EFA	Cogeneration/heat pump facility
von Spakovsky and Evans [30]	EFA	Combined cycle cogeneration
Tsatsaronis and Winhold [31]	EEA	Combined cycle cogeneration
Lozano and Valero [33]	TEC	Simple thermal power plant
Erlach et al. [34]	STT	Combined cycle cogeneration
Valero et al. [36]	Conventional solution	CGAM problem
Tsatsaronis and Pisa [37]	SPECO/AVCO	CGAM problem
Frangopoulos [38]	TFA	CGAM problem
von Spakovsky [39]	EFA	CGAM problem
Valero et al. [40]	TEC	CGAM problem
Lazzaretto et al. [41]	Thermoeconomic diagnosis (TD)	TADEUS problem
Verda [42]	TD	TADEUS problem
Verda and Borchiellini [43]	STT and TD	TADEUS problem
Hua et al. [44]	EEA	Combined cycle cogeneration
Kim et al. [45]	MOPSA	Gas turbine cogeneration system
Cerqueira and Nebra [46]	SPECO/TFA/TEC/TECD	Simple gas turbine cogeneration
Manolas et al. [47]	TFA and genetic algorithm (GA)	Industrial cogeneration system
Lazzaretto and Tsatsaronis [48]	EEA	Combined cycle cogeneration
Kwon et al. [51]	SPECO/MOPSA	Gas turbine cogeneration system
Lazzaretto and Tsatsaronis [52]	SPECO/EEA	Combined cycle cogeneration
Cziesla and Tsatsaronis [54]	IEA—fuzzy logic	Thermal power plant
Kwak et al. [57]	EEA	Thermal power plant
Kwak et al. [60]	MOPSA	CGAM problem
Valdes et al. [59]	TFA and GA	Combined cycle gas turbine plant
Silveira and Tuna [62,63]	EEA and optimization	Combined cycle cogeneration
Vieira et al. [65,75]	STT	CGAM problem
Zhang et al. [67]	STT	Coal fired thermal power plant
Erdil [68]	EEA and optimization	Combined cycle cogeneration
Mazur [69]	EEA—fuzzy logic	Combined cycle cogeneration
Bonnet et al. [70]	EEA	Micro-cogeneration
Colpan and Yesin [73]	SPECO	Combined cycle cogeneration
Li et al. [76]	TFA and optimization	Dist. multi-generation systems
Ozgener et al. [77]	SPECO	Geothermal district heating
Zaleta-Aquilar et al. [78]	EEA	Steam turbine
Unver and Kilic [79]	TEA	Combined cycle cogeneration
Abusoglu and Kanoglu [80,81]	SPECO	Diesel engine cogeneration

6. Exergoeconomic analysis and optimization of combined heat and power production (CHPP)

Combined heat and power production (or cogeneration) is the simultaneous production of power and usable heat from the same fuel or energy source [77,79–81,84]. Cogeneration typically improves the overall efficiency of energy use, leading to reduced fuel use and pollutant emissions, and is an example of distributed generation [84,85]. Depending on the purpose, exergoeconomic studies on combined heat and power production in literature can be grouped in two categories: (1) if the purpose is the allocation and determination of the production costs and/or cost of losses of the plant, the study is focused on the monetary flow rate accounting through components in the plant [4,31,48,57,66,67,70,73,77–81,84]. (2) If the purpose is the optimization of a power system, the study is focused on the selection of the best conditions for operating the system [23–29,36–45,47,50,51,53–55,59–63,64,68,75]. Thermoeconomic concepts and analysis and optimization of combined heat and power production have been studied in a satisfactory amount of works. Among these publications, some specific and remarkable ones are given together with the thermoeconomic method used and type of system studied (Table 11). In the published papers presented in Table 11, several thermoeconomic methods were applied to obtain the unit costs of the products for combined heat and power systems. Application of different methods to a given system normally yields different values of product cost because the assumptions made in the formulations of cost-balance equations are different in each method. Besides, the cost structure of combined heat and power systems is affected by the chosen level of aggregation that specifies the subsystems. The level of aggregation depends on the number of parameters performed in the determination of the unit costs of products [2]. Note that if the irreversibilities in system components are not considered the unit cost of the products does not depend on the chosen level of aggregation [60].

A major fraction of published works listed in Table 11 were performed using algebraic methods [1,4,31,33,37,45,46,51,52,54,60,73,77,80,81]. In these studies, SPECO and MOPSA approaches were applied to combined heat and power systems in order to reduce the subjectivity of fuel and product definitions and cost partitioning. This is done by the help of an iterative exergoeconomic performance improvement procedure based on exergoeconomic variables such as relative cost difference, exergoeconomic factor and exergetic efficiency as introduced by Tsatsaronis [1,2,4,31,33,37].

The remaining studies were performed using calculus methods [22–27,29–34,38,39,44,48,59,70,76,78] mainly developed by Frangopoulos [22–27] and von Spakovsky [29,30,39]. As mentioned before, these methods are based on Lagrange multipliers and they vary from iteration to iteration when thermoeconomic isolation of component is not achieved. This was the main difficulty of the method in the application. After the introduction of functional diagram concept and by assigning only one function and one product to each component by Thermoeconomic Functional Analysis (TFA) method [22–27], the complex nature of the calculus methods were overcome. The Lagrange multipliers show relatively smaller variations in the optimization process with the application of second law in the TFA method [60].

In order to reduce the complexity in the optimization of complex thermal systems, several decomposition methods based on the second law were proposed [44,54,62,63,69]. Combined heat and power systems have some large scale problems due to their complicated nonlinear characteristics. Thermodynamic restrictions make the optimization problem difficult to be solved. Many researchers agree that focusing on the dominant decision variables is more important than manipulating all variables simultaneously in the optimization case [60].

7. Conclusions

Thermoeconomics assesses the cost of consumed resources, money and system irreversibilities in terms of the overall production processes. Methodologies presented through thermoeconomics may help to point out how resources may be used effectively for sustainable development. Assessing the cost of the flow streams and processes in a complex system helps to understand the process of cost formation from the input resources to the final products. These analyses can solve problems related to complex energy systems such as combined heat and power production (CHPP) that could not be solved by using conventional energy analysis.

References

[1] Tsatsaronis G, Lin L, Pisa J. Exergy costing in Exergoeconomics. J Energy Resour-ASME 1993;115:9–16.
[2] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization, 1st ed., New York: Wiley; 1996.
[3] Tsatsaronis G, Moran MJ. Exergy-aided cost minimization. Energy Convers Manage 1997;38:1535–42.
[4] Tsatsaronis G, Ho-Park M. On avoidable and unavoidable exergy destructions and investment costs in thermal systems. Energy Convers Manage 2002;43: 1259–70.
[5] Keenan JH. A steam chart for second law analysis. Mech Eng 1932;54:195–204.
[6] Evans RB. Thermoeconomic isolation and Essergy analysis. Energy 1980;5:805–21.
[7] El-Sayed YM, Gaggioli RA. A critical review of second law costing methods. 1. Background and algebraic procedures. J Energy Resour-ASME 1989;111:1–7.
[8] Gaggioli RA, El-Sayed YM. A critical review of second law costing methods. 2. Calculus procedures. J Energy Resour-ASME 1989;111:8–15.
[9] Tribus M, Evans RL. Thermoeconomics of seawater conversion. UCLA TR 1962;62–3.
[10] El-Sayed Y, Evans RL. Thermoeconomics and the design of heat systems. J Eng Gas Turb Power 1970;92:27–35.
[11] Reistad GM. Availability: concepts and applications. Ph.D. Dissertation. Madison, USA: University of Wisconsin; 1970.
[12] Gaggioli RA. Thermodynamics and non-equilibrium system. Ph.D. Dissertation. Madison, USA: University of Wisconsin; 1961.
[13] Rant Z. Exergie, ein neues wort für technische arbeitsfähigkeit (Exergy as a new word for technical usage). Forchung auf dem Gebiete des Ingeniurwesens 1956;32:36–7.
[14] Baehr HD. Definition und Berechnung von Exergie und Anergie (A useful review of exergy and related concepts). Brenstof-Wärme-Kraft 1965;17: 1–6.
[15] Brodyanski VM. Exergy method of thermodynamic analysis. Energia, Moscow; 1973.
[16] Fratzscher W. Exergy calculations for chemical processes. Energetyka 1978;68: 3–7 [in Polish].
[17] Bergmann E, Schmidt KR. Zur kostenwirtschaflichten optimierung der wärmeaustauscher für die regenerative speisewaservorwärmung im dampfkraftwerk – ein störungsverfahren mit der exergie. Energie und Exergie. Düsseldorf: VDI-Verlag; 1965. p. 63–89.
[18] Szargut J. Grenzen für die anwendungsmöglichkeiten des Exergiebegriffs (Exergy for as system and for a flow process). Brenstof-Wärme-Kraft 1967;19:309–13.
[19] Szargut J. Anwendung der exergie zur angenhärten wirtschaftlichen optimierung. Brenstof-Wärme-Kraft 1971;23:516–9.
[20] Szargut J. Wärmeökonomische probleme des umweltschutzes. Energieanwendung 1974;23:306–10.
[21] Kotas TJ. The exergy method of thermal plant analysis. Krieger Publishing Company 1995 (reprinted with corrections and additions to the first edition of 1985). Malabar, Fla.
[22] Frangopoulos CA. Thermoeconomical functional analysis: a method for optimal design or improvement of complex thermal systems. Ph.D. Thesis. Atlanta, USA: Georgia Institute of Technology; 1983.
[23] Frangopoulos CA. Thermoeconomic functional analysis and optimization. Energy 1987;12:563–71.
[24] Frangopoulos CA. Intelligent functional approach: a method for analysis and optimal synthesis–design–operation of complex systems. J Energy Environ Econ 1991;1:267–74.
[25] Frangopoulos CA. Optimization of synthesis–design–operation of a cogeneration system by the intelligent functional approach. J Energy Environ Econ 1991;1:275–87.
[26] Frangopoulos CA, von Spakovsky MR. A global environomic approach for energy systems analysis and optimization. Part I. Energy Systems and Ecology ENSEC'93, Cracow, Poland; 1993. p. 123–32.
[27] Frangopoulos CA, von Spakovsky MR. A global environomic approach for energy systems analysis and optimization. Part II. Energy Systems and Ecology ENSEC'93, Cracow, Poland; 1993. p. 133–44.

[28] von Spakovsky MR. A practical generalized analysis approach to the optimal thermoeconomic design and improvement of real-world thermal systems. Ph.D. Thesis. Atlanta, USA: Georgia Institute of Technology; 1986.
[29] von Spakovsky MR, Curti V. The performance optimization of a cogeneration/heat pump facility. ECOS'92, ASME, New York, USA; 1992.
[30] von Spakovsky MR, Evans RB. Engineering functional analysis—Parts I, II. J Energy Resour-ASME 1993;115:86–99.
[31] Tsatsaronis G, Winhold M. Exergoeconomic analysis and evaluation of energy conversion plants. Part I. A new general methodology. Part II. Analysis of a coal-fired steam power plant. Energy 1985;10:69–94.
[32] Valero A, Lozano MA, Munoz M. A general theory of exergy saving I, II and III. New York, USA: ASME Books; 1986. p. 1–21.
[33] Lozano MA, Valero A. Theory of the exergetic cost. Energy 1993;18:939–60.
[34] Erlach B, Serra L, Valero A. Structural theory as standard for thermoeconomics. Energy Convers Manage 1999;40:1627–49.
[35] Tsatsaronis G. Exergoeconomics: is it only a new name? Chem Eng Technol 1996;19:163–9.
[36] Valero A, Lozano MA, Serra L, Tsatsaronis G, Pisa J, Frangopoulos C, et al. CGAM problem: definition and conventional solution. Energy 1994;19:279–86.
[37] Tsatsaronis G, Pisa J. Exergoeconomic evaluation and optimization of energy systems—application to the CGAM problem. Energy 1994;19:287–321.
[38] Frangopoulos CA. Application of the thermoeconomical functional approach to the CGAM problem. Energy 1994;19:323–42.
[39] von Spakovsky MR. Application of engineering functional analysis to the analysis and optimization of the CGAM problem. Energy 1994;19:343–64.
[40] Valero A, Lozano MA, Serra L, Torres C. Application of the exergetic cost theory to the CGAM problem. Energy 1994;19:365–81.
[41] Lazzaretto A, Toffolo A, Reini M, Taccani R, Zaleta-Aquilar A, Rangel-Hernandez V, et al. Four approaches compared on the TADEUS (thermoeconomic approach to the diagnosis of energy utility systems) test case. Energy 2006;31:1586–613.
[42] Verda V. Accuracy level in thermoeconomic diagnosis of energy systems. Energy 2006;31:3248–60.
[43] Verda V, Borchiellini R. Exergy method for the diagnosis of energy systems using measured data. Energy 2007;32:490–8.
[44] Hua B, Chen QL, Wang P. A new exergoeconomic approach for analysis and optimization of energy systems. Energy 1997;22:1071–8.
[45] Kim SM, Oh SD, Kwon YH, Kwak HY. Exergoeconomic analysis of thermal systems. Energy 1998;23:393–406.
[46] Cerqueira SAAG, Nebra SA. Cost attribution methodologies in cogeneration systems. Energy Convers Manage 1999;40:1587–97.
[47] Manolas DA, Frangopoulos CA, Gialamas TP, Tsahalis DT. Operation optimization of an industrial cogeneration system by a genetic algorithm. Energy Convers Manage 1997;38:1625–36.
[48] Lazzaretto A, Tsatsaronis G. On the calculation of efficiencies and costs in thermal systems. Proc ASME Adv Energy Syst Div 1999;39:421–30.
[49] Bejan A, Badescu V, De Vos A. Constructal theory of economics. Appl Energ 2000;67:37–60.
[50] Rodriguez-Toral MA, Morton W, Mitchell DR. Using new packages for modeling, equation-oriented simulation and optimization of a cogeneration plant. Comput Chem Eng 2000;24:2667–85.
[51] Kwon YH, Kwak HY, Oh SD. Exergoeconomic analysis of gas turbine cogeneration systems. Exergy 2001;1:31–40.
[52] Lazzaretto A, Tsatsaronis G. Comparison between SPECO and functional exergoeconomic approaches. In: Proceedings of the ASME international mechanical engineering congress and exposition – IMECE/AES-23656; November 2001. p. 11–6.
[53] Toffolo A, Lazzaretto A. Evolutionary algorithms for multi-objective energetic and economic optimization in thermal system design. Energy 2002;27:549–67.
[54] Cziesla F, Tsatsaronis G. Iterative exergoeconomic evaluation and improvement of thermal power plants using fuzzy inference systems. Energy Convers Manage 2002;43:1537–48.
[55] Ionita I. Engineering and economic optimization of energy production. Int J Energy Res 2002;26:697–715.
[56] Bejan A. Fundamentals of exergy analysis, entropy generation minimization, and the generation of flow architecture. Int J Energy Res 2002;26:545–65.
[57] Kwak HY, Kim DJ, Jeon JS. Exergetic and thermoeconomic analyses of power plants. Energy 2003;28:343–60.
[58] Chejne F, Restrepo JA. New rules for the exergo-economic optimization methodology. Energy 2003;993–1003.
[59] Valdes M, Duran MD, Rovira A. Thermoeconomic optimization of combined cycle gas turbine power plants using genetic algorithms. Appl Therm Eng 2003;23:2169–82.
[60] Kwak HY, Byun GT, Kwon YH, Yang H. Cost structure of CGAM cogeneration system. Int J Energy Res 2004;28:1145–58.
[61] Sciubba E. Cost analysis of energy conversion systems via a novel resource-based quantifier. Energy 2003;28:457–77.
[62] Silveira JL, Tuna CE. Thermoeconomic analysis method for optimization of combined heat and power systems, part 1. Prog Energy Combust 2003;29:479–85.
[63] Silveira JL, Tuna CE. Thermoeconomic analysis method for optimization of combined heat and power systems, part 2. Prog Energy Combust 2004;30:673–8.
[64] Frangopoulos CA, Dimopoulos GC. Effect of reliability considerations on the optimal synthesis, design and operation of a cogeneration system. Energy 2004;29:309–29.
[65] Vieira LS, Donatelli JL, Cruz ME. Integration of an iterative methodology for exergoeconomic improvement of thermal systems with a process simulator. Energy Convers Manage 2004;45:2495–523.
[66] Uhlenbruck S, Lucas K. Exergoeconomically-aided evolution strategy applied to a combined cycle power plant. Int J Therm Sci 2004;43:289–96.
[67] Zhang C, Wang Y, Chuguang Z, Xinsheng L. Exergy cost analysis of a coal fired power plant based on structural theory of thermoeconomics. Energy Convers Manage 2006;47:817–43.
[68] Erdil A. Exergy optimization for an irreversible combined cogeneration cycle. J Energy Inst 2005;78:27–31.
[69] Mazur VA. Fuzzy thermoeconomic optimization. Exergy 2005;2:1–13.
[70] Bonnet S, Alaphilippe M, Stouffs P. Energy, exergy and cost analysis of a micro-cogeneration system based on an Ericsson engine. Int J Therm Sci 2005;44:1161–8.
[71] Lazzaretto A, Tsatsaronis G. SPECO: a systematic and general methodology for calculating efficiencies and costs in thermal systems. Energy 2006;31:1257–89.
[72] Cardona E, Piacentino A. A new approach to exergoeconomic analysis and design of variable demand energy systems. Energy 2006;31:490–515.
[73] Colpan CO, Yesin T. Energetic, exergetic, and thermoeconomic analysis of Bilkent combined cycle cogeneration plant. Int J Energy Res 2006;30:875–94.
[74] Paulus DM, Tsatsaronis G. Auxiliary equations for the determination of specific exergy revenues. Energy 2006;31:3235–47.
[75] Vieira LS, Donatelli JL, Cruz ME. Mathematical exergoeconomic optimization of complex cogeneration plant aided by a professional process simulator. Appl Therm Eng 2006;26:654–62.
[76] Li H, Nalim R, Haldi PA. Thermal-economic optimization of a distributed multi-generation energy system—a case study of Beijing. Appl Therm Eng 2006;26:709–19.
[77] Ozgener L, Hepbasli A, Dincer I, Rosen MA. Exergoeconomic analysis of geothermal district heating systems: a case study. Appl Therm Eng 2007;27:1303–10.
[78] Zaleta-Aquilar A, Correas-Uson L, Kubiak-Szyszka J, Sierra-Espinosa FZ. Concept of thermoeconomic evaluation of steam turbines. Appl Therm Eng 2007;27:457–66.
[79] Unver U, Kilic M. Second law based thermoeconomic analysis of combined cycle power plants considering the effects of environmental temperature and load variations. Int J Energy Res 2007;31:148–57.
[80] Abusoglu A, Kanoglu M. Exergetic and thermoeconomic analyses of diesel engine powered cogeneration. Part 1. Formulations. Appl Therm Eng 2009;29:234–41.
[81] Abusoglu A, Kanoglu M. Exergetic and thermoeconomic analyses of diesel engine powered cogeneration. Part 2. Applications. Appl Therm Eng 2009;29:242–9.
[82] Abusoglu A, Kanoglu M. First and second law analysis of diesel engine powered cogeneration systems. Energy Convers Manage 2008;49:2026–31.
[83] Parida PK, Gupta DK. An improved regula-falsi method for enclosing simple zeros of non-linear equations. Appl Math Comput 2006;177:769–76.
[84] Rosen MA, Minh NL, Dincer I. Efficiency analysis of a cogeneration and district energy system. Appl Therm Eng 2005;25:147–59.
[85] Spiewak S. Cogeneration and small power production manual, 5th ed., France: Lavoisier Inc.; 1997.